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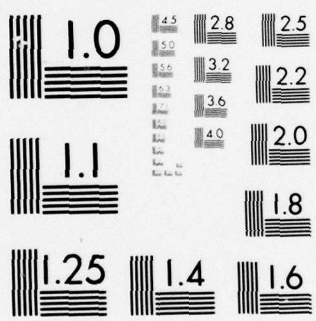

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AN UNCERTAINTY ANALYSIS APPROACH TO IMPROVING SENSOR SYSTEMS MIXES

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Systems Analysis Office

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US ARMY ELECTRONICS COMMAND FORT MONMOUTH, NEW JERSEY 07703

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A continuation of the development as a decision tool of a methodology for evaluating tactical intelligence producing systems. The basic decision is concerned with how to commit available funds to obtain the best sensor mix in terms of intelligence producing capabilities. In this exercise certain cost and operational constraints are established and defined. Pertinent information parameters used are presented and explained. Both quantitative improvements, i.e., procuring additional sensors; and qualitative

improvements, i.e., developing sensors with higher probabilities of detection are considered in this exercise. The analysis consists of deriving equations which relate enemy activity, equipment detectability, number of sensors, quality of sensors, and cost to the relative probability of detection of various equipments in a US mechanized division. These relative probabilities are used to construct matrices which relate unit types to equipment. The entropy transform ($H = -P \log_2 P$) is applied to these matrices and information theoretic measures are derived. These measures are then used as a basis for deciding among available sensor mixes. Further development and problem areas are also discussed.

equals

Introduction.

This work is a continuation of the development of a methodology which utilizes information theory or uncertainty analysis to evaluate tactical intelligence producing systems. This particular exercise will explore the impact of qualitative and quantitative changes in the intelligence systems sensor mix on certain information theoretic parameters. Within certain cost and operational constraints, these informations theoretic parameters will indicate which of a set of alternatives would most likely give the greatest intelligence benefit. These indications would allow a decision maker to rationally commit resources to the development and/or procurement of additional sensor systems.

Prior to beginning the exercise, it would be beneficial to relate a number of important points as mentioned in previous work (5). Tactical or combat intelligence is that information that is required by a commander to plan and conduct tactical operations (2). The information from which this intelligence is derived is contained in the data that is produced by the system's sensors. The precise method that is used to sift the information from the data, and in turn the intelligence from the information, has not been clearly defined. This shortcoming is not of critical importance in the technique to follow. What is important is the fact that intelligence is highly situational in that it depends on the desires of the commander and the operational constraints in which he operates. Information theory is useful in this construct since it deals with the statistics of the data and not with the meaning or interpretations of any data received or sent. The technique in (5) is flexible enough to allow for variations in operational constraints as well as in the intelligence demands of the commander. This flexibility is useful in applying a number of decision options to a wide range of environments, situations and "scenarios." Information theory or uncertainty analysis possesses a number of advantages which are more clearly explained in (1) and (4).

As explained in (5), an essential criteria of a viable intelligence system is the amount of potential intelligence that is contained in the data produced by the system's array of sensors. The data as it is received from the field establishes pattern which gives indications of the enemy's intentions and deployments. With these intentions and deployments the commander is able to plan and conduct tactical operations. These patterns of sensings are dependent not only on enemy activity, but are also highly affected by our use and development of sensors. For example, when considering the total number of sensings, a high percentage of vehicular sensings may give indications of enemy movements; or it may be due to our over sensitizing our sensor system to vehicular movements as opposed to other detectable activity. Consequently, an intelligence analyst, when attempting to perceive the enemies deployment from a series of sensor data, must be able to discern which patterns are due to enemy activity and which patterns are due to the idiosyncrasies of the sensor system.

Some characteristics of the sensor system which affect this pattern are the various numbers of sensors able to detect each equipment category, and the relative quality of the sensors within each equipment category. This exercise will explore how a decision maker can improve the intelligence system's ability to produce intelligence by adjusting the mix of sensors or by improving the quality of the sensors within the system. To avoid mathematical and computational complexities this exercise will remain relatively simple and will draw upon the work done in (5). Even though the technique has the capability of N-dimensions, this exercise will be developed only in the two-dimensional construct. The essential points and relationships can be made within these limitations.

The following example will deal with a scenario in which a division commander needs to know the locations and type of the enemy brigade and higher headquarters, the battalion size elements, and the air defense units so that he can conduct a rivercrossing operation. The enemy is organized and trained very similarly to a US mechanized division. To provide this planning information, the friendly division is equipped with sensor systems that can detect and differentiate tracked vehicles, wheeled vehicles, radar sets, aircraft, indirect fire weapons, and FM radio transmitters. Again, the essential question is how much potential information about units is contained in data about equipment? By adjusting our sensor mix it is possible to improve the information capacity of the data.

As with most conventional armies, they are constrained by Tables of Organizations and Equipment (TOE), logistics restrictions, and tactics. Consequently, the enemy division does not distribute its equipment equally or randomly among the various units of the division. This constraint forces these conventional armies to operate in such a way as to produce certain patterns. This pattern allows an intelligence analyst to infer the enemy's deployment with incomplete knowledge.

From the TOE of a US mechanized division, it is possible to construct the following probability matrix which is the probabilities of occurrence of various equipment and units in the division.

If each type of equipment was equally detectable, then we would expect to detect the equipment in the percentages indicated in Table 1. Since there are about 7400 equipment items in the division, then we could obtain the actual number of equipment items in each category or unit type by multiplying 7400 by each of the probabilities in the matrix. For example, there are .1219 x 7400 = 902 track vehicles in the manuever units. There are .3704 x 7400 = 2,741 wheeled vehicles in the divisions. And there are .1472 x 7400 = 1,089 detectable items in the artillery units.

Table I

Probability of Occurrence

	Track	Wheeled	Radar	Aircraft	Indirect Fire	Trans-mitter	Σ
Manuever	.1219	.1196	.0100	.0035	.0134	.2682	.5367
Artillery	.0234	.0745	.0005	.0000	.0100	.0388	.1472
Air Defense	.0070	.0130	.0016	.0000	.0000	.0174	.0391
Headquarters	.0051	.0291	.0000	.0039	.0000	.0266	.0648
Service	.0095	.1342	.0000	.0016	.0000	.0669	.2122
Σ	.1669	.3704	.0122	.0091	.0134	.4180	

Probability of Detection.

Now if our sensor system detected each equipment class with equal likelihood, then we would expect to detect equipment in the ratios as shown in Table 1. However, there are a number of factors which change or distort the pattern of detections. In general, the probability of detection is not the same as the probability of occurrence. This difference is affected not only by what the friendly side does, but by what the enemy side does. If the enemy does not use certain categories of equipment or if his discipline is such that he does not expose his equipment, the friendly side will make fewer detections in those categories. Also if the friendly side has few sensors or low quality sensors, then again there will be few detections. Before an item of equipment can be detected, it must in some way be exposed. That is, the enemy must use it, move it, or in some way emit or reflect some type of energy so as to allow a detection. If the enemy does not in some way expose his equipment, it cannot be detected. Conversely, if the friendly side has no sensors then again there will be no detections.

Another factor in assessing the probability of exposure is the equipment itself. Certain types of equipment are highly "visible" on the battlefield. An artillery piece makes loud noises and sends a shell along a calculable trajectory. A scanning radar emits a high energy beam which can be detected relatively easily. In contrast, a radio transmitter can transmit on varying frequencies for short periods, and can be directionalized. In general, the probability of exposure can be described as follows:

$$Pex = F(K, L, N)$$

where: Pex = probability of exposure

K = factor reflecting enemy tactics, discipline, training, etc.

L = factors reflecting relative energy emissions of an equipment.

N = number of sensors.

Exactly what the functional relationship between Pex and K, L and N is not clear. Pex should increase as enemy activity increases. Also as N increases Pex should approach 1.0. For lack of any empirical data, let me postulate the following equations:

$$\text{let } Pex = K\,(1 - e^{-N/L}) \qquad (1)$$

where $0 \leq Pex \leq 1.0$

$0 \leq K \leq 1.0$

Operating under this relationship, Pex will approach 1.0 as $N \rightarrow \infty$ and as $L \rightarrow 0$. The relationship (N/L) represents the interaction of the number of sensors and the relative detectability of the various equipment.

The probability of exposure (Pex) as postulated gives a measure of the degree to which the enemy exposes his equipment and the relative opportunity that the friendly side has to make detections.

The probability of detection (Pd) in turn reflects the actual number of correct sensings that occur when an enemy equipment comes within the range of a friendly sensor. The probability of detection (Pd) and the probability of exposure (Pex), as defined above, are independent. Therefore, the probability of detecting an exposed equipment is:

$$Pdex = Pd \cdot Pex \qquad (2)$$

That is, if the enemy exposes 90% of a certain equipment type and our sensors detect 80% of that equipment type that comes within its range, then Pdex = .90 x .90 = .72. In this case we would expect 72% of a certain category of equipment to be detected at least once during any time period. Therefore, if the enemy has 150 tracked vehicles, we would only expect .72 x 150 = 108 detections during any time period. Conversely, if the friendly side made 108 detections with a sensor system constrained and defined as above, the friendly side should deduce that the enemy has about 150 tracked vehicles in the area. At any rate, utilizing the above relations, it is possible to derive the expected number of detections of a certain equipment type per time period as follows:

$$Pdex_i \times E_{ij} = Ed_{ij} \qquad (3)$$

where:

$Pdex_i$ = probability of detecting an exposed type i equipment.

E_{ij} = number of equipment type i in type j unit

Ed_{ij} = expected number of type i equipment detected in time period in type j unit.

For example, if the enemy's TOE states that he has 100 transmitters in the Air Defense units and Pdex for transmitters is .80, then we would expect to detect 80 transmitters per time period on the average.

Summing over both i and j will give us the expected total sensings per time period.

$$\sum_{ij} Ed_{ij} = Ed_{tot} \qquad (4)$$

Summing only over i or j will give the expected number of sensings in equipment category and the expected number of detections per unit category, respectively.

Dividing the various E_{ij} factors by ED_{tot} will give the normalized probabilities of detection of the various equipment and units.

$$P(E_{ij}) = ED_{ij}/Ed_{tot} \tag{5}$$

With this equation it is then possible to construct a probability matrix similar to Table I, but with the probability of detection and not the probability of occurrence.

Having this matrix, it is then possible to apply Shannon's measure for average information.

$$H_{ij} = - P(E_{ij}) \log_2 P(E_{ij}) \tag{6}$$

where H_{ij} is the average entropy, uncertainty, or information associated with $P(E_{ij})$. The result of this transform is an entropy matrix which will allow the derivation of a number of information theory measures that will give insights into the relative information quantities in the data.

The measures which will be tested in the analysis to follow shall be $H(U)$, $T(U|E)$, efficiency, and $H(U|E)$. These measures should be sufficient to give a rational basis for allocation of resources to develop and procure sensor systems.

$H(U)$ is the average uncertainty as to unit type. It is defined as follows:

$$H(U) = \sum_i \left[\sum_j P(E_{ij}) \quad \log_2 \sum_j P(E_{ij}) \right] \tag{7}$$

This measure reflects the difficulty or uncertainty of identifying unit types from the data available. The greater $H(U)$ is, the more information is required to abolish or reduce the uncertainty.

$T(U|E)$ is the average amount of information transmitted from the equipment data to the unit types. It is closely related to the correlation coefficient in variance analysis (3). This term is commonly called the transmission factor, mutual information or mutual constraint. It reflects the amount of uncertainty about unit type that is reduced with knowledge of the equipment type and vice-versa. It is defined as:

$$T(U|E) = H(U) + H(E) - H(U,E) \tag{8}$$

where:

$$H(E) = \sum_j \left[\sum_i - P(E_{ij}) \log_2 \sum_i P(E_{ij}) \right]$$

$$H(U,E) = \sum_i \sum_j - P(E_{ij}) \log_2 P(E_{ij})$$

Efficiency reflects the relative information carrying capability of the data. It is defined as:

$$\text{Efficiency} = T(U|E)/H(U) \tag{9}$$

If the intelligence system were 100% efficient, according to this definition, the knowledge about equipment would completely resolve our uncertainty about units. Conversely, if efficiency is zero then the data about equipment tells us nothing about units.

Lastly $H(U|E)$ is the average uncertainty remaining as to unit type once the information concerning equipment has been taken into account. It is the average uncertainty left after we gleaned the information available in the data. $H(U|E)$ is defined as:

$$H(U|E) = H(U) - T(U|E) \tag{10}$$

This measure reflects the average confusion remaining concerning units given the data concerning equipments.

With the above relationships and measures, it is possible to get a relatively good assessment of the effects of any changes in the array of sensor systems. By analyzing the change in the information theory measures, the relative benefit or detriment of any decision option can be rationally assessed.

Operational and Cost Constraints.

As mentioned previously, this exercise will deal with a division commander who needs to know the locations and type of the enemy's battalion sized maneuver units, the brigade and higher headquarters, the air defense units, and the artillery and service units. To gain this information, the intelligence system has an array of sensors that can detect and differentiate tracked vehicles, wheeled vehicles, radar sets, aircraft, indirect fire weapons, and FM radio transmitters. To further define the operational environment, let us assume that at present the typical friendly division has the following number of sensors which can detect the previously defined categories of equipment. Also, let us assume the following values for Pd and L.

TABLE II

Sensor Category	N	Pd	L
Tracked Vehicles	400	.90	1123
Wheeled Vehicles	400	.80	277
Radar Sets	6	.90	3.73
Aircraft	12	.60	33.7
Indirect Fire Weapons	8	.80	15.7
Radio Transmitters	6	.70	8.66

All of these values are arbitrary and can be changed readily. To further simplify let us also assume that the enemy uses all his equipment in the time period. In other words in all instances K = 1.0.

With these parameters defined, it is now possible to generate a probability matrix based on the probability of detecting exposed equipment. Table III was generated using the previously derived equations, particularly equation 5.

In comparing this table with Table I, it can be seen how our sensor system changes or distorts the patterns of detection from the patterns of occurrence of the equipment. In comparing the marginal probabilities along the bottom of the tables, it can be seen that our sensor system makes wheeled vehicles and radar sets more prominent than their normal probability of occurrence; and makes the other categories of equipment relatively less visible in comparison to their probability of occurrence. When comparing the marginal probabilities along the right of the tables, the equipment in the other type units becomes more visible. At this point it is not clear whether these changes or distortions are beneficial or detrimental.

Decision Constraints.

Assuming the above conditions as a baseline, how can the above system be adjusted so as to give maximum benefit? Suppose a decision maker has available $15M to acquire additional sensors or to improve the sensor's sensitivity to augment the intelligence producing capability of the Army's divisions. To keep the analysis simple the decision maker will commit the funds to only one option and to only one sensor type. Therefore, all the funds will be spent to either acquire more sensors of any one type or will be used to improve the quality of any one type. In essence, the decision maker has the option of either increasing N_i or of increasing Pd_i. Concerning N_i, this can be related to the funds available by the following equation:

TABLE III

Probabilities of Detection

	Tracks	Wheels	Radar	Air-craft	Indirect Fire	Trans mitter	
Manuever	.0756	.1682	.0139	.0015	.0098	.2159	.4849
Artillery	.0145	.1055	.0007	.0000	.0074	.0312	.1593
ADA	.0044	.0182	.0027	.0000	.0000	.0140	.0393
HQ	.0032	.0409	.0002	.0016	.0000	.0214	.0673
Service	.0059	.1888	.0000	.0007	.0000	.0539	.2492
	.1036	.5216	.0175	.0037	.0172	.3364	

$$\$ = C_i \; Na_i \qquad (11)$$

where $\$ = \$1M$ per division

C_i = unit cost of sensors

Na_i = number of additional sensors of type i

Assuming there are 15 divisions in the Army, then each division would get \$1M worth of additional sensors. When Na_i is added to N_i and the various probabilities calculated, there will be some effect on the various information measures.

The other option of increasing Pd_i will approach only 1.0 as the amount spent on the quality of the sensors increases indefinitely. For lack of any emperical data the following relations between Pd_i and the funds available as postulated.

$$S = C_i^* \left[e^{\frac{1}{1-Pd_i}} - e \right] \qquad (12)$$

where C_i^* = constant reflecting the relative ease of making qualitative improvements

\$ = total dollars spend on development

With this equation when $Pd_i = 0$, then \$ = 0, and when \$ = 00 then Pd will approach 1.0. For the sake of simplicity, it will be assumed that \$20M has been spent on each of the sensor systems to achieve the Pd_i as stated in Table II. The addition of \$15M will then increase Pd_i according to the relation in equation 12.

Analysis.

The essential question which the decision maker must resolve is how to gain the most intelligence benefit from the \$15M in available funds. The method to be examined here is to invest all the money in either a quantitative or qualitative improvement in any one of the six sensor categories.

The sensor array as described in Table II and the resultant probability matrix in Table III give the following uncertainty measures when the entropy transforms (equation 6 through 10) are applied:

$H(U) = 1.8737$ bits, $T(U|E) = .1289$ bits, Eff = 6.8779%

$H(U|E) = 1.7448$ bits

This essentially is the base line to which any changes should be compared. With the sensor system as it is presently formulated, the above is the average information theoretic measures forthcoming from the system. The objective of the exercise, then, is to gain the maximum improvement in these measures with the available money.

Approaching the quantitative improvements first, if we apply the money to each of the various sensor categories so as to increase the number of sensors in each category in turn, the following results are achieved.

TABLE IV

QUALITATIVE OPTIONS

Sensor Category	Number of Sensors A	B	C	D	E	F
Tracked Vehicles	1400	400	400	400	400	400
Wheeled Vehicles	400	1400	400	400	400	400
Radar Sets	6	6	16	6	6	6
Aircraft	12	12	12	25	12	12
Indirect Fire Weapons	8	8	8	8	28	8
Radio Transmitters	6	6	6	6	6	16

Generating probability matrices and the subsequent entropy measure for each of the above sensor mixes give the following results.

TABLE V - EFFECTS OF QUANTITATIVE CHANCES

Option	H(U) bits	T(U|E) bits	Efficiency %	H(U|E) bits
A	1.8316	.1411	7.7053	1.6905
B	1.8983	.1215	6.4004	1.7768
C	1.8730	.1314	7.0166	1.7416
D	1.8753	.1312	6.9965	1.7441
E	1.8709	.1400	7.4811	1.7309
F	1.8345	.1175	6.4057	1.7170

In examining the results in Table V, it appears that option A gives the most benefits. H(U) and H(U|E) have decreased, while T(U|E) and efficiency have increased. Option A gives the lowest conditional uncertainty, i.e., H(U|E), and the highest efficiency and transmission factor. This option also gives significant improvements over the baseline measures.

When applying the available funds to qualitative improvements of the sensor systems so as to increase the probability of detection (equation 12) for each sensor category in turn, the following table of sensor parameters is received.

TABLE IV - QUALITATIVE OPTIONS

Probability of Detection (Pd)

Sensor Category	OPTION A	OPTION B	OPTION C	OPTION D	OPTION E	OPTION F
Tracked Vehicles	.9053	.9000	.9000	.9000	.9000	.9000
Wheeled Vehicles	.8000	.8199	.8000	.8000	.8000	.8000
Radar Sets	.9000	.9000	.9053	.9000	.9000	.9000
Aircraft	.6000	.6000	.6000	.6621	.6000	.6000
Indirect Fire Weapons	.8000	.8000	.8000	.8000	.8199	.8000
Radio Trans-mitters	.7000	.7000	.7000	.7000	.7000	.7000

Again generating new probability matrices and the resulting entropy measures gives the following table.

TABLE VII - EFFECTS OF QUALITATIVE CHANGES

OPTIONS	H(U) bits	T(U|E) bits	Efficiency %	H(U|E) bits
A	1.8735	.1289	6.8827	1.7446
B	1.8759	.1283	6.8438	1.7476
C	1.8759	.1285	6.8473	1.7475
D	1.8761	.1288	6.8633	1.7474
E	1.8761	.1260	6.9774	1.7471
F	1.8724	.1282	6.8454	1.7443

In reviewing this table it can be seen that there has been very little effect caused by investing the money in qualitative improvements. If an option can be picked out as the best, it appears that Option A gives the most benefit. However, when the best quantitative option is compared to the best qualitative option, it is clear that the quantitative improvements give the most relative intelligence benefit. Therefore, based on the above operational and cost constraints as stated above, quantitative Option A will give the best improvement in the intelligence system on the average.

Discussion.

The above analysis and the resulting conclusion are highly restrictive and simplified. The methodology used can be greatly expanded both in scope and in complexity. The essential point was to determine that decisions concerning an information acquisition and processing system for the military can be dealt with in a rational, nonintuitive manner. The variables used in the above analysis deal with the sine qua non of intelligence processing, the information and data. Cost is an ever present variable in any analysis and was duly considered. Such ancillery variables as weight, power consumption, capacity and other logistical variables were not considered, but may be of importance to implementing any decision.

With more statistical support and more resources, the above analysis could have been expanded to cover additional dimensions such as spatial deployments of units, different types of divisions, different types of activities, double detections, false alarms, and the varying intelligence demands of a commander. If the above expansions are undertaken. the conclusions reached may change dramatically.

The equations derived in the above analysis are applicable to both static and dynamic conditions (1). If data or studies were available to determine the average capacity of a Tactical Operations Center (TOC), this above type of analysis would be useful in determining the input parameters of the overall operational and intelligence processing capacity of any given unit. Conant (1) has derived a number of partitioning rules which may prove highly useful in evaluating and designing tactical information processing systems and procedures.

The equations in the above analysis that were postulated (equation 1 and 12), were done so in an attempt to separate out the various factors that influence the patterns of detection received in a TOC. At present little empirical research or data has been collected to support or refute these relations. Neither has there been much effort to collect empirical data so as to more precisely define such variables and constants as Pex, the probability of exposure; K, the relative activity of the equipment; nor L, the relative detectability of various equipment. Consistent measures and scales for all equipment categories need to be defined and used. The use of simulation and computer models could contribute greatly to more precise definitions of the above relations and constants.

In conclusion, the above exercise and analysis is an attempt to lend some structure to the tactical intelligence problem. It provides a framework for further research and analysis. Hopefully, further work will contribute to a better understanding and subsequently better designs and utilization of tactical automated information and intelligence systems.

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